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Experimental
Techniques for
Electron Scattering
Investigations

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Experimental Techniques for Electron Scattering Investigations

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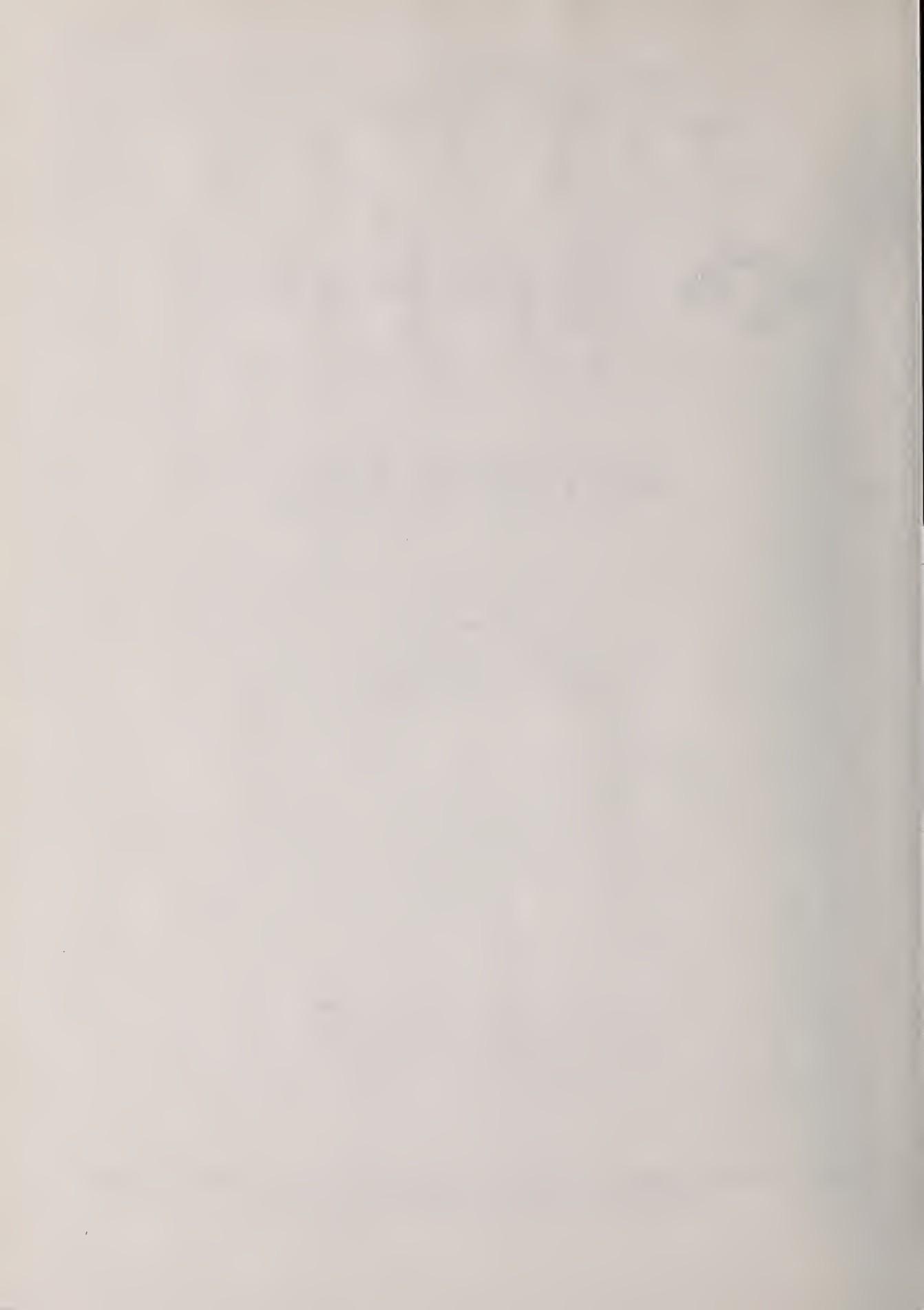
FOREWORD

This report was originally prepared for presentation at a Seminar on the subject "Nuclear Investigations on Linear Electron Accelerators at Low and Medium Energy," held at the P. N. Lebedev Physical Institute, Moscow, USSR, December 10-16, 1969. The paper presents a fairly extensive review of modern techniques used in the performance of electron-nucleus scattering experiments with electron linear accelerators in the 50 to 1000 MeV range, and particularly of the NBS facility which has not been fully described elsewhere. The paper is therefore reproduced here in its original form in order to be available to a wider audience.

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Experimental Techniques for Electron Scattering Investigations

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Modern experimental techniques for high energy electron scattering are discussed. Subjects included are: high resolution spectrometer design, the energy loss spectrometer concept, detector ladder systems, beam current monitoring techniques, suppression and measurement of background, the use of on-line computer systems, theoretical considerations and the analysis of data, and 180° scattering.

Key words:background; current monitoring; detector ladders; electron scattering; experimental techniques; line-shape fitting; on-line computer systems; radiative tails; resolution; spectrometer design.

1. Introduction

For many years it has been said that electron scattering is a powerful tool for the study of nuclear structure, because quantum electrodynamics is a very accurate theory and because the weakness of the electromagnetic interaction allows accurate theoretical interpretation of experimental results. In spite of these advantages, electron scattering has in the past contributed little to our understanding of the nucleus, in contrast to the vast amount of information obtained by reaction studies employing nuclear particles (protons, alphas, etc.). This situation has changed greatly in recent times, and electron scattering is at last proving its great value as an experimental technique for the study of nuclear properties.

As a result of recent improvements in experimental techniques and apparatus we are now able to perform detailed and accurate experiments which yield valuable information on nuclear structure. For example, figure 1 shows a recently-obtained spectrum of electrons inelastically scattered from Ti^{48}[1]/* compared to an inelastic alpha scattering experi-

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*Literature references at the end of this paper.

ment on the same nucleus. We can see from figure 1 the the resolution, peak-to-background ratios, and the states excited in the two experiments are quite comparable.

The main reasons that we are now able to perform experiments of this quality are: (1) the development of the modern electron linear accelerator which provides high current, small beam energy spread, good beam emittance, and improved duty cycle compared to earlier machines; (2) better understanding of the principles of beam transport which allows us to obtain well resolved, stable electron beams of high quality[2/]; (3) improvements in the design and construction of magnetic spectrometers to obtain high resolution and good acceptance (solid angle times useful momentum range along the focal plane); (4) the development of multi-channel "ladder" detector systems; (5) improved methods of beam current monitoring; and (6) the use of on-line computer systems, enabling us to handle the enormous quantity of data obtained and to effectively control and monitor the progress of the experiment.

In this paper we will report on the present state-of-the-art in the experimental techniques mentioned above. We will also refer briefly to developments in electron scattering theory as they apply to the interpretation of experimental data, and discuss some current problems such as the treatment of backgrounds.

2. Spectrometer Design

The properties of an electron scattering facility are largely determined by the parameters of the magnetic spectrometer which is used. We will begin our discussion by listing the major design requirements for a spectrometer. First, good resolution is essential. As shown in Table I,

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many factors contribute to the overall resolution of the system. Not only must the intrinsic resolution of the spectrometer be good, but large dispersion is required so that detectors and beam spots of reasonable dimensions can be used. Second, because low cross sections are an ever-present problem, large solid angle and momentum acceptance are needed. Third, the spectrometer should be useable over a broad range of both momentum and scattering angle to permit measurement of both longitudinal and transverse form factors over an extended range of momentum transfer. Fourth, the geometry of the spectrometer must allow for good shielding of the detector system because we must measure very small cross-sections in the presence of very high backgrounds.

Ten years ago the standard instrument for electron scattering was the 180° n=1/2 double focussing spectrometer[3]. It provided a resolution of 0.1 to 0.2% with a solid angle of order .005 steradians and, since the double-focussing property results in a small detector volume, it was relatively easily shielded. With the advent of the high current electron linac, we could afford to define a smaller momentum bin in the beam transport system, use thinner targets to reduce energy-loss straggling, and still have reasonable counting rates. It was then necessary to design spectrometers to take advantage of the better resolution capability thus available. We chose the "magic angle spectrometer"[4] because it provides good resolution while retaining all the desirable properties of the 180° spectrometer. This spectrometer, shown in figure 2, is now in use at NBS. Similar spectrometers are in use at Amsterdam[5], Tohoku (Japan), and Glasgow. A spectrometer of slightly modified design providing smaller aberrations in the transverse (scattering) plane and a larger

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useful momentum acceptance is being installed at Saclay[6/].

The resolution obtainable with the magic angle spectrometer is demonstrated in figure 3, which shows inelastic scattering data from the first two excited states of O^{16} from a 35 mg/cm^2 beryllium oxide target[7/]. The overall resolution of about 60 keV (full width at half-maximum) results from a total instrumental resolution of 48 keV (0.08 percent of the incident energy) plus a contribution due to energy loss straggling.

I do not want to give the impression that the magic angle spectrometer is the only design which is suitable for high resolution electron scattering work, because there are in fact many other possibilities. I want to mention here one entirely different design, the "energy loss spectrometer" being built at MIT[8/]. The MIT spectrometer is a uniform-field, 90° deflection split-pole type, designed for a momentum resolution capability of about one part in 10^4 over a 2% interval, and a solid angle of about 5msr[9/]. The important difference of the MIT design from conventional spectrometers is that the transverse optics provides "point-to-parallel" rather than "point-to-point" focussing. The reason for this choice is that for large momentum transfers and light target nuclei the kinematic broadening of the resolution for a reasonable acceptance angle in the scattering plane is large. By employing point-to-parallel focus-sing, knowledge of the scattering angle is preserved, and thus a correction can be made for the kinematic broadening. A possible disadvantage of this approach is that one of the methods for handling the "instrumental background" is not possible here. This will be further discussed in section 5.

While we are discussing the MIT design, I would like to comment on

the energy-loss system which the MIT group plans to use. The basic principle is illustrated in figure 4, which is taken from reference 8. In this system, the beam transport arrangement provides a momentum-dispersed (but spacially focussed) beam at the spectrometer target location. If this dispersion is properly matched to the imaging and dispersion properties of the spectrometer then all electrons which have lost a given amount of energy in the target arrive at a single point in the spectrometer focal plane, independently of their initial energy. Since good resolution in energy loss is the essential requirement in electron scattering, the energy loss system allows one to use a larger portion of the current from the linac while maintaining good resolution. Thus the advantage of this system is that it permits much higher counting rates whenever beam current is the limiting factor. I want to emphasize that the energy loss system <u>does</u> <u>not</u> allow a relaxation in the resolution requirements of either the beam transport system or the spectrometer. In fact, it may be more difficult to obtain the needed resolution because some spectrometer aberrations, which are not significant when the beam spot size at the target is small, are important for the larger spot size of the dispersed beam.

There are some general principles of spectrometer design which are important regardless of the specific optics. In order to obtain the optical properties called for in the design it is necessary to obtain the required magnetic field configuration to a high degree of accuracy[10/]. Obtaining the desired field configuration is particularly difficult in electron scattering because the spectrometer must be useable for a large range of particle momenta, and thus a large range of field strengths.

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Differential saturation of the iron can distort the field distribution

drastically when the field strength is changed. One method of minimizing

this effect is to use the "Rogowski profile" for the edge of the magnet

poles[11]. To simplify the construction problem, it may be adequate to

approximate the Rogowski profile by one or two plane segments at the

edges. This is the procedure used in the NBS spectrometer, as shown in

figure 5. We have shown that the optical properties of this spectrometer

do not change appreciably in the range of field strengths between 0.9kG

and 13kG (in our case this corresponds to momenta between about 20 and

290MeV/c).

In order to fully use the high resolution properties of the spec-

trometer, the magnetic field must be stable to a small fraction of the

resolution width. Stabilities of one part in 10^5 or better are obtained

from conventional well regulated power supplies. Figure 6 demonstrates

the current stability of the NBS spectrometer. When taking data we

routinely measure the spectrometer current (actually the voltage across

a series "shunt" resistor held at constant temperature by water cooling)

along with our count rate measurements at intervals of typically one to

three minutes. We do not routinely measure the magnetic field in the

spectrometer directly as is done in most other laboratories. As a matter

of fact it is not obvious that a single point magnetic field measurement

should be more precisely proportional to electron momentum than is a cur-

rent measurement. Our procedure is to follow a prescribed path along the

hystersis curve of the iron by "cycling" the spectrometer. This provides

a reproducibility of momentum for a given spectrometer current within

one or two parts in 10^4 when the spectrometer is recycled[12]. When taking

typical inelastic scattering spectra, peaks corresponding to known energy
levels are observed to occur at the proper electron energy, typically
within ±5keV.

3. Detector Systems

The main requirements placed on detector systems for scattered elec-
trons are: small size in the dispersion direction to take full advantage
of the resolution, stability of counting efficiency, good rejection of
background events, and the ability to operate at high instantaneous
counting rates. It is highly desirable to use many counting channels,
not only to improve the data accumulation rate, but to minize cross-
section errors due to variations of beam energy, spectrometer magnetic
field, or beam current. The first multichannel detection system, or
"ladder counter" for electron scattering work was developed at Stanford
by H. W. Kendall[13/]. The basic idea is that a number of small detectors
are located along the focal plane of the spectrometer in order to detect
the position at which each electron intersects the focal plane. Thus
each detector corresponds to a slightly different momentum bin of scat-
tered electrons for any given magnetic field in the spectrometer.

The ability to handle high counting rates (in each detector) is very
important in electron scattering for two reasons. First, it is often
necessary to obtain good statistical precision for the net area of a
small peak superimposed on a large continuum (e.g., due to the radiative
tail of the elastic peak). Secondly, it is often desirable to normalize
inelastic scattering cross sections to the elastic scattering cross sec-
tion which may be many orders of magnitude larger. Better accuracy can
be obtained when it is possible to avoid making large changes in the

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beam current between the elastic and inelastic measurements.

Several different types of detectors have been used successfully in ladder systems, including plastic scintillators, semiconductors, and multi-wire spark chambers or proportional counters. We will describe these types of ladder counters briefly here and compare the advantages and disadvantages of each type. We refer to the literature for more detailed descriptions.

Plastic scintillator ladders offer the advantages of high count rate capability due to the fast response and rapid recovery of the scintilla-tor-phototube combination. When a coincidence requirement between the counters in the ladder and a "back-up" detector (usually a large Cerenkov Counter) is included in the system, the background rejection properties are good. However, it has been demonstrated that if suf-ficient care is taken in reducing the background, plastic scintillator detectors can be used effectively with no coincidence requirement[14] (at least when the electron beam energy is low). The main problem with plastic scintillators in high resolution systems is that the detectors must be very small, making it difficult to get enough light to the photo-tube to have a satisfactory signal-to-noise ratio. It is also difficult to package a scintillator system compactly, because of the necessity for light pipes and the relatively large size of phototubes which should be as close to the scintillators as possible.

Counter ladders employing lithium-drifted silicon semiconductor detectors were first used for electron scattering at NBS[15,16]. A semi-conductor ladder is also in use at the Tohoku linac, and a large semi-conductor system is in preparation at Saclay. It is relatively easy to

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make semiconductors very small (the dimensions of the present NBS detectors are $1 \times 1.25 \times 60mm^3$), and pack them close together in a ladder. Since appropriate preamplifiers can be made very small, expecially if integrated circuits are used, the entire array is quite compact compared to a scintillator-phototube system and therefore is easier to shield. Semiconductor systems are in general not as fast as phototube systems, but if the detectors are cooled to liquid-nitrogen temperature, charge collection times of about 20ns can be obtained. The NBS counters have a coincidence resolving time of 50ns and a dead time of 80ns. With the aid of auxiliary circuitry to measure chance counts and dead-time corrections, our system is useable at high counting rates and in severe background-to-true count rate situations [12,15]. Two disadvantages of semiconductor detectors are their sensitivity to radiation damage and to surface contamination. Because of these effects, the detector efficiencies can change (over a period of some weeks or months), and eventually the detectors must be replaced. This is not too serious because the detectors themselves are inexpensive, and replacing them is not difficult. In the NBS system, the useful detector lifetime seems to be roughly one to two years.

Spark chambers of various types have also been employed as ladders counter[17, 18]. The spatial resolution of spark chambers is about the same as semiconductor detectors; they are just as compact, and the electronic readout system is simpler. A great many channels can be built since the cost per channel is relatively small. Counting rate limitations and poor background rejection seem to be the main disadvantages of spark chambers. I am not aware of any system of this type which is capable of

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recording more than one count per linac beam pulse per channel, whereas phototube systems and even semiconductors can record several events per pulse for beam pulse lengths of a few microseconds[39].

A serious problem with any multichannel array is to determine the detection efficiencies of the individual detectors. The problem is severe with detectors of very small size because a substantial fraction of the incident particles pass through or near the edges, thus producing pulses which are smaller (and perhaps of a different shape) than the pulses due to particles passing through the center of the detector. Unless one is willing to be committed to a data taking procedure in which all detectors in the ladder are eventually located at all electron momemtum values in the spectrum desired, a means must be found for accurately intercomparing the efficiencies of all detectors. The usual procedure for obtaining the efficiencies is to measure the counting rates due to a flat, or at least reasonably smooth, spectrum of scattered electrons. From data taken in all detectors at several closely spaced spectrometer field settings, the relative efficiencies of the detectors can be determined[19]. A different procedure can be used when provision is made for mechanically moving the detectors along the focal plane. One simply moves the ladder so that each detector occupies the position previously occupied by its neighbor and compares the counting rates of each pair of adjacent detectors under identical experimental conditions[15]. By combining these two procedures it is possible to distinguish intrinsic differences between the detectors from a number of contributing effects such as variation of solid angle and dispersion along the focal plane and loss of efficiency due to multiple scattering of electrons in the small detectors

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(resulting in some electrons not reaching the back-up detector, an effect which can be important for low energy electrons).

The ability to move the detectors along the focal plane has other useful features. When the resolution is good, only a few detectors see a peak in the spectrum at one magnetic field setting. For an isolated level, this is not very important since only the area of a peak is physically significant, but for closely spaced levels or small peaks superimposed on a continuum, many points closely spaced in energy are needed to distinguish contributions from each level and/or the continuum. With a movable ladder, it is easy to space data points very closely by small changes in the detector position. Of course, such changes can also be accomplished by changing the magnetic field but is seems to us to be easier to mechanically move the detectors a precisely determined distance reliably and reproducibly. In the NBS system, the precision of detector motion corresponds to 2 parts in 10^6 in momentum, which would be very difficult to achieve or measure with magnetic field changes.

A separate, but related, problem is the determination of the absolute efficiency of the detector system which is necessary if absolute cross sections are to be measured. Absolute electron scattering cross sections are rarely measured, but in fact can be traced back to the assumed accuracy of the Rosenbluth formula for elastic electron-proton scattering together with the experimentally known proton form factors[20/]. At NBS we have demonstrated the feasibility of a method for determining the absolute efficiency of our detector system which involves the use of an auxiliary "area" detector in the focal plane which is much larger in the dispersion direction than the detectors in the ladder. The area detector

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determines the area of a scattering peak without precise knowledge of detector edge effects, since only a very small fraction of electrons in the peak pass near the edges. The small detectors can be compared to the area detector by a series of measurements in which the detectors are moved along the focal plane. From this data the efficiencies of the small detectors are determined relative to the area detector, and the small influence of edge effects on the latter can be removed iteratively. To complete the determination of absolute efficiencies, it is necessary to study in detail the response of the area detector as well as the plastic scintillators in coincidence with it. This is done by determining pulse height spectra, variations of count rates with detector collection voltage or phototube high voltage, and by other standard techniques.

4. Current Monitoring

Accurate beam charge measurement is essential to any cross section determination. A Faraday cup together with an electronic integrating circuit provides good absolute accuracy, but introduces several problems if used during the course of the scattering measurements. The problems are: (1) the cup is a very strong source of background; (2) at low energies, multiple scattering in the target may prevent some of the electrons in the beam from reaching the cup; and (3) if used continuously, the cup must be cooled to remove the heat due to the beam power. Because of these difficulties, most laboratories employ other types of current monitors, which must be calibrated against the Faraday cup. The two most commonly used monitors are the secondary emission monitor (SEM), and the ferrite pulse transformer. Although good results have been reported with the SEM[21/], we have not had much success with them at NBS.

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We believe that our high beam current causes changes in the surface properties of the foils in the SEM, resulting in erratic behavior and substantial variations in calibration during data taking.

A ferrite-core pulse transformer provides a good measurement of beam pulse current, and produces no background since the beam is not intercepted. Electronic integration of the signal to obtain the beam charge is more difficult than in the case of a Faraday cup because the signals are smaller and A. C. coupled. Appropriate integrating circuits have been developed[22/] which provide charge measurement precision of about ±0.2 percent for currents of the order of 0.5μA or larger. The limiting factor seems to be how well electrical pickup (primarily due to the linac modulators) can be suppressed[23/].

An interesting technique for current measurement is in use at Amsterdam, employing a ferrite pulse transformer together with a Faraday cup[24/]. The Faraday cup is located far enough from the experimental target so that it can be well shielded. A pair of quadrupole magnets collects the multiple-scattered electron beam from the target to maximize the fraction of the beam reaching the cup. A known multiple of the current collected by the cup is passed back through the ferrite so as to cancel the beam current pulse[25/]. A measurement of the charge collected by the Faraday cup together with a knowledge of the multiplying factor which produces a null signal from the ferrite provides an accurate measure of the beam charge delivered to the target. This method is illustrated in figure 7.

A similar procedure is used at NBS to measure the absolute charge collection efficiency of our Faraday cup. Measurements now being made

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by J. S. Pruitt of our laboratory indicate that the cup, whose dimensions are based on the work of Kantz and Hofstadter[26/], is large enough to contain essentially all of the charged secondaries produced by the beam. He also finds that ther is a small (<1%) but energy-dependent loss of charge due to backscattering of electrons through the entrance of the cup, and that there is a small (~.5%) _increase_ in charge collected in the cup due to collection of secondary electrons generated by electron-electron scattering in the entrance vacuum window of the cup. By applying corrections for these measured effects, we believe we can determine the absolute efficiency of our Faraday cup to an accuracy of better than 0.1%.

<div align="center">5. Background Considerations</div>

Suppression of background counts in the detector system is essential for accurate cross-section measurements. We distinguish three main sources of background which must be considered.

First, there is the room background generated primarily at the place the electron beam, having passed through the target, is finally absorbed. This type of background is handled by shielding the Faraday cup (as mentioned already in section 4), or by using a non-intercepting monitor (or SEM) and carrying the residual beam to a well shielded "beam dump". Shielding directly around the detectors is obviously necessary also. At NBS our main shielding consists of 20cm of lead and 10cm of boron loaded polyethylene. The room background which does penetrate the shielding is mostly neutrons and thus produces many more singles counts in the individual detectors than it does coincidence counts which might be interpreted as good events. Thus the main effect of room background in our case is to produce electronic dead times. This amounts to roughly 2%

dead time per microamp of beam current when the Faraday cup is in the beam, and 0.5% per microamp when the cup is not in the beam. We feel that we can make deadtime corrections to better than 20% of their value, thus permitting 1% counting accuracy at 10μA beam current.

A second source of background is degraded electrons and x-rays in and around the main electron beam, which can scatter from the target and enter the spectrometer, besides contributing to the room background[27]. Suppression of this type of background depends mainly on good beam handling technique[2].

The third and most serious type of background is that due to scattered electrons which enter the spectrometer but have an energy such that they can not reach the detectors directly, but instead scatter from the pole tips and vacuum chamber walls of the spectrometer. This "instrumental scattering" background is worst when attempting to measure a small inelastic peak which is a few percent (in scattered electron energy) away from a strong elastic scattering peak. This type of background can be reduced by at least three approaches as follows: (1) A system of baffles is installed in the spectrometer to reduce the number of electrons striking the vacuum chamber walls and to absorb the scattered electrons which do strike the walls[12], as shown in figure 8. (2) Making use of the double-focussing property of the spectrometer one moves the detectors transversely (out of the spectrometer midplane) so that electrons coming from the target do not pass through them, and measures the background directly[14]. Obviously this method is not available if the spectrometer optics does not produce a transverse-plane image of the target in the focal plane, as in the MIT system discussed above (in section 2). (3) The

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instrumental scattering is greatly reduced by using a thin-walled vacuum chamber and moving the magnet return yoke away from the immediate vicinity of the magnet poles, as in the Mainz spectrometer[28/]. A combination of these methods should be better than any one of them. Therefore at NBS, where we use the baffle technique, we plan to replace our present detector ladder with a two dimensional array so that we can simultaneously measure good events and instrumental background.

6. Data Handling with On-Line Computer Systems

In high resolution electron scattering, enormous quantities of data must be recorded and analyzed. In a typical experiment on the low-lying levels of a light nucleus, one would spend perhaps six hours to obtain a spectrum for a single incident energy. In order to obtain data at sufficiently closely spaced momentum intervals and to obtain data for several detectors at each momentum value (to be able to extract relative detector efficiencies as discussed in section 3, and to make the results relatively insensitive to the accuracy of the efficiency intercomparison) we would use some 200-300 different combinations of magnetic field setting and detector ladder position. A typical spectrum of this type is shown in figure 9. At NBS we have a 20 channel ladder, so that for each of these 200 or so "runs" we must record 40 numbers (including such quantitites as beam charge, run time, spectrometer shunt voltage, counts in auxiliary channels for dead time corrections, etc., in addition to the counts in 20 channels). I can say from experience that it would just not be feasible to take data of this type without some type of automatic data handling equipment.

In addition to collecting the data, the computer serves several

other important functions. It can be programmed to perform a set of runs automatically. For example, the computer at NBS monitors the beam charge continuously and terminates the run (by turning off a master counting gate) when a predetermined charge has been collected. It then computes the results of the run, types out the data and records them on magnetic tape for further use, clears all temporary data storage, moves the detectors and/or changes the spectrometer field as desired, and turns on the master counting gate for the next run. The experimenter, being freed of all these routine operations, has time to study the results as they are obtained and thus can intelligently determine the best way to proceed with the experiment. In order to make these decisions, the experimenter should have the results available on-line. This means that the computer must analyze the data during and between runs. At NBS we can choose any data field in the computer for observation as an oscilloscope display. We might choose to look at the counts in the detectors of the ladder displayed as a histogram while the data are being accumulated. More often, we would watch one of several spectra, corresponding to different targets or to analysis of one spectrum in various size momentum bins. These spectra are updated by the computer after each run. The data of each run are corrected for such things as counting rate effects and detector efficiency differences and added to the previously-existing spectra in units of counts per MeV per unit beam charge. A typical spectrum of this type is shown in figure 10. These are actually the same data as in figure 9 except that the results from all detectors has been combined and divided into uniform momentum bins. This particular spectrum was obtained by off-line reanalysis of data on a different computer,

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using as input a punched-paper tape record produced by the on-line system. Reanalysis is necessary because detector efficiencies and backgrounds are determined during the course of the experiment, so that the on-line analysis relies on provisional values based on past experience which may not be highly accurate. Several different computers have been used for reanalysis, including the on-line system.

I do not want to describe any particular computer system in detail, however I would like to mention some of the general features of the NBS system[29/]. We chose a modular approach to the programming, as well as to the hardware, in order to have a system with maximum flexibility. The system is used for all the physics experiments done with our linac including neutron time-of-flight spectroscopy, charged particle electroproduction experiments (such as (γ,p) and (γ,d)), and several others besides electron scattering. Very little programming must be done for any particular experimental setup because with the modular concept most programs (executive system, display of various kinds, etc.) are used by all experiments. Most changes of experimental procedure or equipment do not require additional programming. For example, when we converted our detector ladder from 12 to 20 channels, no original programming was needed, although several simple modifications in existing programs were made to accomodate the additional channels of information. The multilevel priority interrupt feature of our system is extremely valuable. It permits several experimenters to use the computer simultaneously. (Although possible, this is not actually done very much because of memory size limitations, and only one experiment is usually done with the linac beam at one time.) More important, the interrupt feature permits assign-

ment of priorities to the many functions performed by the computer in one experiment. For example, all data taking functions are assigned higher priority than the display function, and the magnetic tape data recording is done at higher priority than the typing of results since the tape record is more useful than the printout.

Finally, I should like to point out that on-line computers for experiments with pulsed accelerators need not necessarily be extremely fast because the time between beam pulses is available for computation. The computer at NBS has a memory cycle time of $8\mu s$ (the memory is 16,000 - 24 bit words). In electron scattering, about one millisecond is used between beam pulses for data accumulation, and about 5 seconds between runs for calculation of spectra, recording of data on tape, and changing of experimental conditions.

7. Theoretical Considerations

Although the subject of this paper is experimental techniques, there are certain theoretical questions which bear directly on the analysis and interpretation of experimental data, and therefore should be mentioned. These questions are more urgent now than they would have been a few years ago because of the increasing accuracy of recent experiments.

Radiative corrections are discussed in detail in the recent review article by Maximon[30]. From the experimentalist's viewpoint, it appears that the corrections are well enough understood for the reliable interpretation of experimental data at the level of about one percent accuracy. To go beyond this level of accuracy seems to be very difficult theoretically, and also difficult to verify experimentally. The reason it is difficult to verify the corrections experimentally is that even with the

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best resolution presently available, the largest contribution to the correction occurs at values of the radiative energy loss within the experimental resolution width, and thus is not directly accessible experimentally. It will be interesting to test the validity of the corrections with the improved resolution expected at the new Saclay and MIT facilities. (The only experimental test I know of is to measure the area of a scattering peak as a function of the integration end point ΔE, calculate the radiative correction for each value of ΔE, and check for consistency.)

Dispersive corrections can be important in both elastic and inelastic scattering, particularly in the vicinity of diffraction minima[30/]. I know of no unambiguous experimental measurements of dispersive effects, although there is one experiment in progress which might turn out to show an effect. Accurate elastic scattering measurements on the titanium isotopes (46, 48, 50) have been made at both NBS[31/] and Stanford[32/], but the momentum transfer corresponding to the first diffraction minumum was obtained by quite different combinations of scattering angle and beam energy in the two experiments. Dispersive effects are expected to be energy dependent and might be expected to be particularly large in this case because of the presence of very strong collective E2 transitions to low-lying excited states in these isotopes. The inelastic cross section reaches a peak at momentum transfer values near the first elastic cross section minimum.

As we continue to improve experimental resolution capability, we will attempt to measure the cross-sections for more closely spaced nuclear levels. Thus we will continue to be faced with the problem of determining the separate cross-sections of peaks in the spectrum which

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are not fully resolved. To do this accurately requires a line-shape analysis. I want to briefly describe the procedure developed by J. C. Bergstrom[7,33/]. The calculation includes the effects of Landau straggling (ionization energy losses), small angle bremsstrahlung, radiation emitted during the large angle scattering, and the experimental resolution. The computer program which has been developed finds the best fit to one or more peaks in the spectrum plus continuum (radiative tails and background). The parameters which can be found by the least squares analysis are peak height, peak energy location, target thickness (in terms of Landau straggling width), and resolution width (assumed to be a gaussian function). Alternatively any one or more of these parameters may be fixed, allowing the program to find best values for the remaining ones. For example, if the difference in energy of two levels is accurately known, the peak heights can be determined more accurately. In the case of levels which have a physical width comparable to or larger than the resolution, the physical width can be determined separately if the experimental resolution is known (say from the analysis of a nearby narrow peak in the spectrum). The curves in figures 3 and 11 are generated by this line-shape program.

In order to determine inelastic scattering cross-sections the radiative tails due to all processes at lower excitation must be subtracted from the observed spectrum. This subtraction is relatively unimportant in the case of resolved peaks, but must be done very well to obtain accurate cross section information in the continuum region (for examples, the giant dipole resonance and quasi-elastic scattering). The best available radiative tail calculations[34/] are performed in Born approxi-

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mation. These calculations give excellent agreement with experimental results for the first few MeV of the spectrum in the case of carbon targets with incident energies of 50 to 150 MeV, and scattering angles as large as about 160 degrees[14,27]. When thick target effects (bremsstrahlung and electron-electron scattering) are included, the agreement between calculation and experiment is within about 3% in the above-mentioned limited range of parameters. More important is the question of whether the calculated tail is correct for the entire spec-trum. Figure 12 illustrates a case where the agreement appears to be better than 10% for the entire spectrum. In this example the absolute scale of the calculated tail is based solely on the observed elastic scattering cross section; there is no arbitrary normalization. This spectrum was measured with an incident energy of 69MeV from a carbon target at a scattering angle of 75°. At higher energies and more backward angles the agreement gets progressively poorer[12]. This effect is not necessarily due to a failure of the radiative tail theory but could just as well be caused by the increasing importance of backgrounds and the relatively greater importance of the nuclear continuum cross section. Very little is known about the validity of radiative tail calculations in heavier nuclei, where the Born approximation may not be very good. More work in this area, both theoretical and experimental, is needed in order to understand the situation.

Until rather recently, electron scattering cross sections of light nuclei were conventionally analyzed in the framework of the Born approx-imation using plane-wave electron wave functions. (The failure of the Born approximation per se is discussed above where the effect is refer-

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red to as dispersive corrections.) Even in the lightest nuclei however

the plane wave approximation is only good to about ten percent. Futher-

more the distorted wave corrections depend on the multipolarity of the

transition and thus do not cancel in the ratio of inelastic to elastic

cross sections. A number of investigators have studied the problem of

distorted wave effects[35/], and accurate computer programs have been

developed to perform the calculations by phase-shift analysis using

relativistic coulomb wave functions, for both elastic and inelastic cross

sections. In comparing experimental results, one must be sure to under-

stand how each experiment was analyzed. We should be very careful when

presenting experimental data to state very explicitly when and how

distorted wave corrections are made.

8. Electron Scattering at 180°

In my opinion there has been a tendency among some of our colleagues

to overestimate the value of 180° scattering experiments. The reason

for this is basically that the cross sections due to transverse effects

(magnetic or transverse electric) do not increase at backward angles

(at fixed momentum transfer the cross section actually decreases by about

30% between 150° and 180°); thus when the scattering angle is large

enough that errors due to subtracting continuum tails from the trans-

verse cross section peaks are unimportant, there is no point in going to

more backward angles. The optimum angle depends on resolution, counting

rate, and background as well as on the ratio of transverse to coulomb

cross sections (which we know to be essentially $\tan^2 \theta/2$). My point is

that we can do better in terms of resolution, counting rate, and back-

ground at conventional angles. The reasons are: (1) Up to about 150°

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targets can be oriented for transmission geometry rather than the reflec-tion geometry needed for 180° scattering, giving for a fixed target thickness, a factor of nearly four in the effective thickness (hence, counting rate), and simultaneously better energy resolution because in transmission geometry only the Landau straggling contibutes to the energy spread, instead of the spread in energy loss corresponding to twice the target thickness which occurs in reflection. (2) It is usually necessary to severely limit the solid angle in 180° experiments.

Scattering experiments at 180° are valuable as a part of a more general program, for those special cases where transverse and large coulomb cross sections are present at the same excitation energy. I refer here particularly to magnetic elastic scattering[36/], and certain special cases of inelastic scattering such as the Ml contribution to the electro-disintegration of the deuteron near the breakup threshold.

9. Summary

We have tried to summarize in this report the advances in exper-imental techniques which have led to major recent improvements in the accuracy and reliability of electron scattering data. In our opinion the most important of these advances are those in the areas of resolution, detector systems, beam current monitoring, background suppression, the use of on-line computers, and higher counting rates (resulting largely from the development of the high-current electron linac). In many experiments a limiting factor at present is the difficulty of obtaining suitable (in terms of thickness, uniformity, and stability) target materials, especially in the case of separated-isotope targets. I believe that in the very near future we will see the results of the

recent advances in experimental techniques, in the form of the greatly
improved understanding of nuclear structure which can be gained by
electron scattering studies.

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39. Note added in proof: Very recent work at Saclay indicates that the count rate limitation of multiwire proportional chambers can be improved by the use of electronegative gases in the chambers. This group has observed resolution times near 30ns and counting rates of the order of 10^7 per second. See: "Multiwire Proportional and Semiproportional Counter with a Variable Sensitive Volume" C. Grunberg, L. Cohen, and L. Mathieu, preprint, Service de Physique Nucleaire a Haute Energie, Centre d'E tudes Nucleaires de Saclay. We thank Prof. W. Bertozzi for calling this paper to our attention.

Table I

EFFECTS CONTRIBUTING TO OBSERVED RESOLUTION

The resolution factors listed are deduced from experimental data obtained with the NBS electron scattering facility. The percentages are given as full width at half maximum (FWHM) values relative to the incident beam energy. The effects listed should be added in quadrature to obtain the overall resolution (.07 percent, minimum). The starred entries are the FWHM resolutions of gaussian distributions which would give the same contributions as the actual rectangular distributions[37]. The target referred to here is 20 mg/cm^2 polyethylene, $(CH_2)_n$, and the values quoted are for incident energies 60-100 MeV and scattering angles 90-145 degrees.

FACTOR		PERCENT
I.	Beam Transport	
	Entrance Aperture	.04-.09*
	Energy Slits	varies
	Intrinsic	.04
II.	Spectrometer	
	Detector Size	.03*
	Intrinsic	.03
	Beam Spot Size	.02
III.	Target	
	Kinematics	.01-.02*
	Energy Loss Straggling	.01-.02
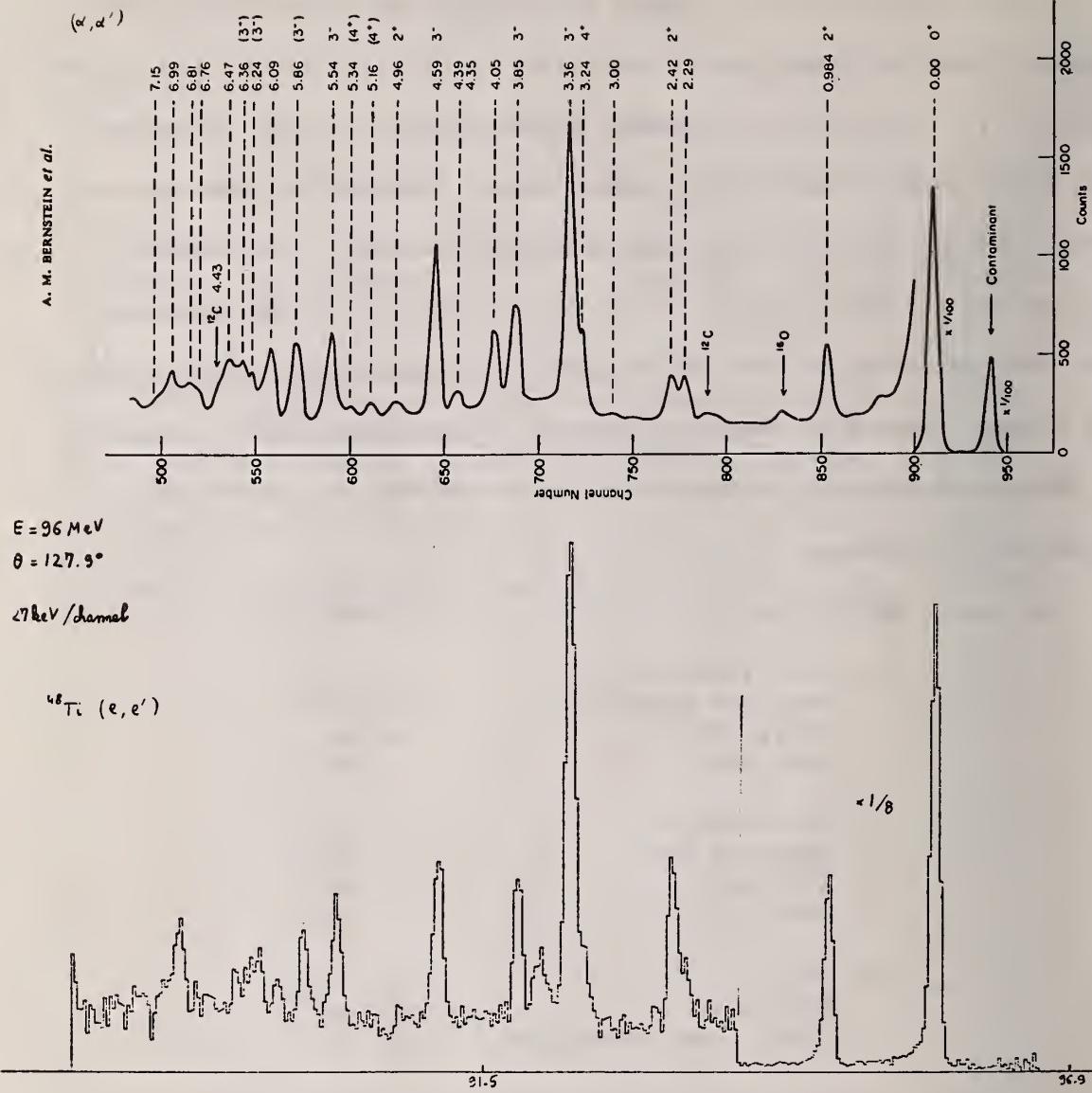
Figure 1. Spectrum of electrons scattered from Ti^{48} (lower figure) compared to alpha particle spectrum from the same nucleus. The energy scales for the two figures have been made equal. Vertical scales are arbitrary. The (α,α') data is taken from the paper of A. M. Bernstein, et al., Nucl. Phys. A115, 79 (1968).

30
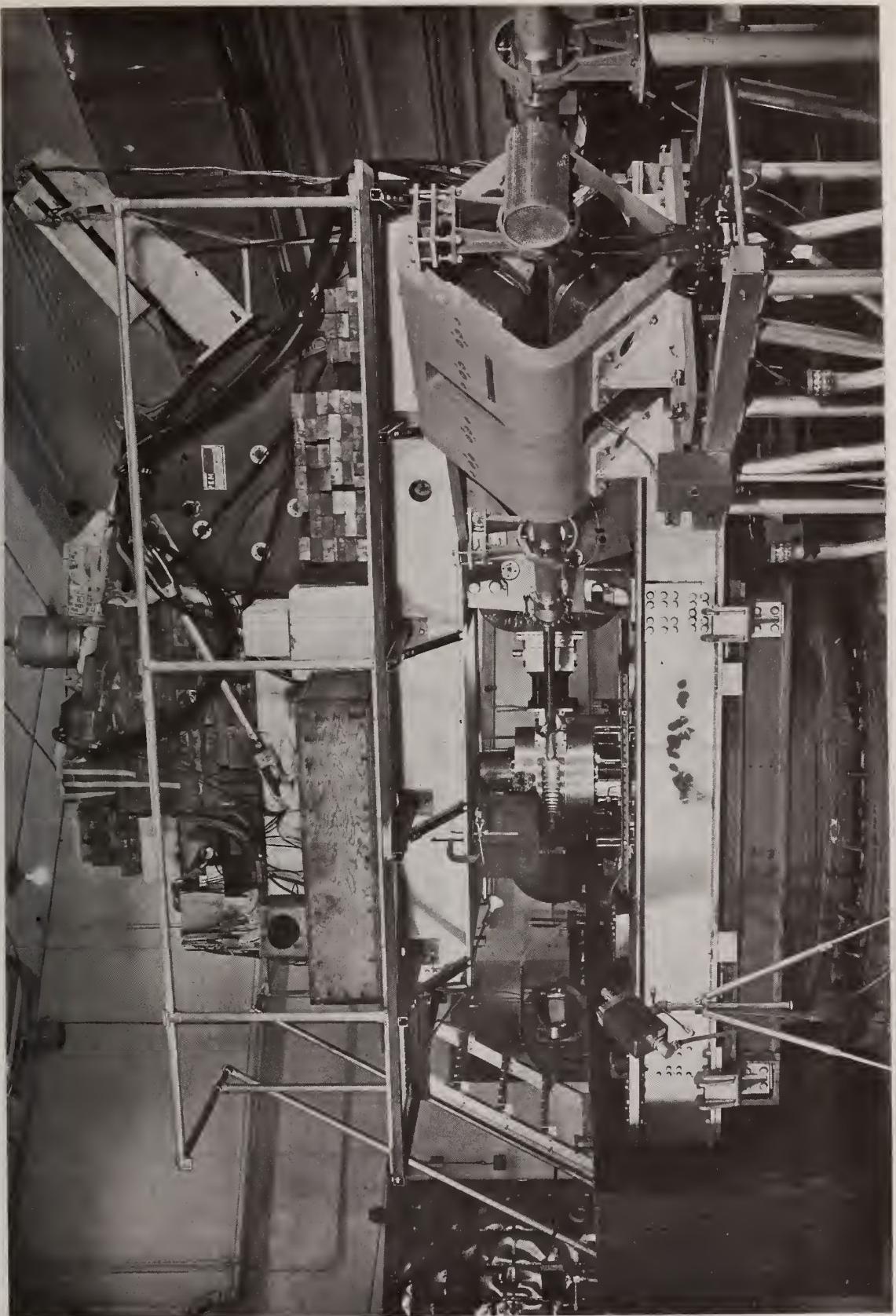
Figure 2. The NBS Electron Scattering Spectrometer
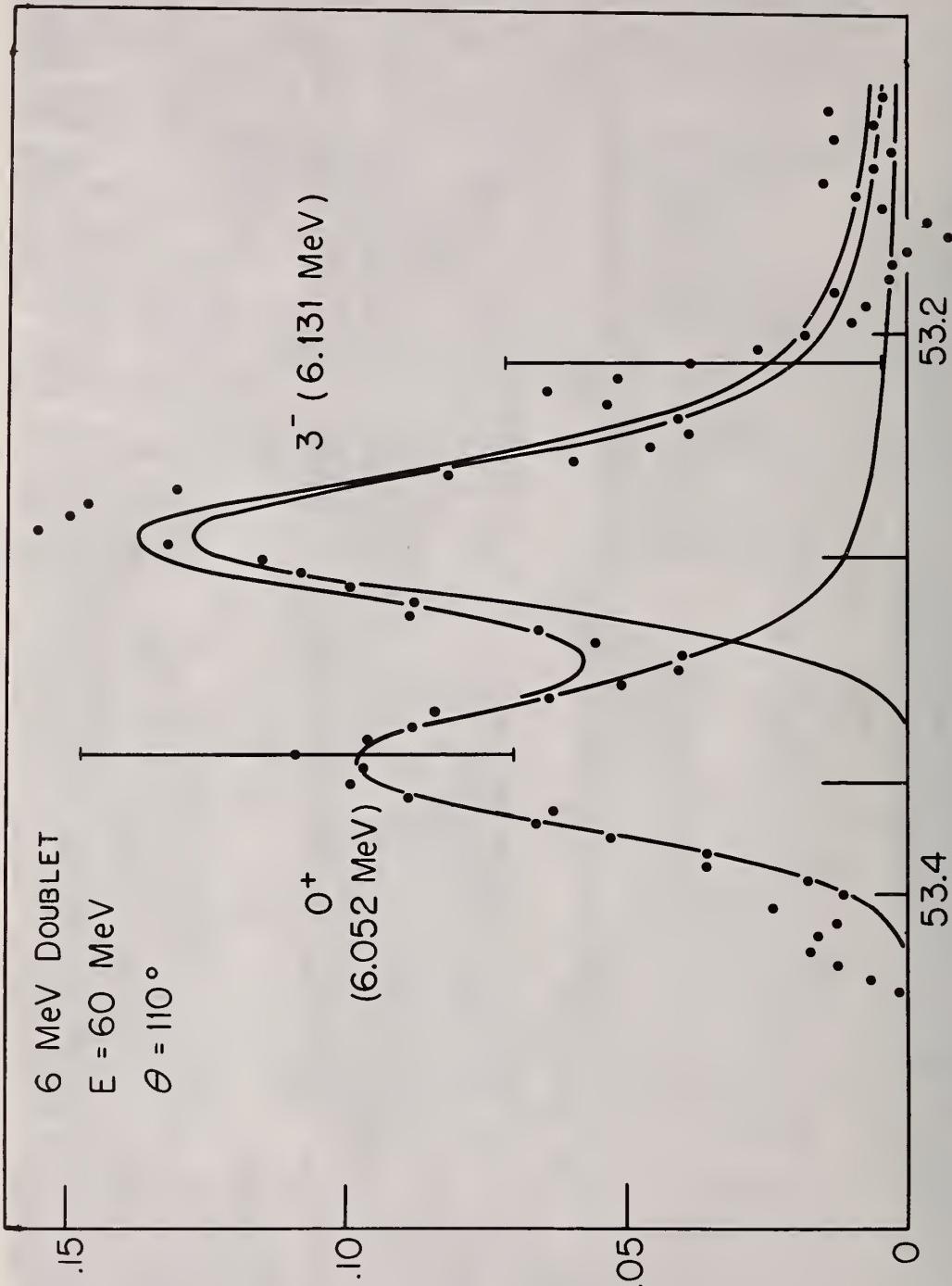
Figure 3. High resolution electron scattering data on the first two excited states of O^{16}. Elastic radiative tails and background have been subtracted. Instrumental resolution is 48keV (.08%). The solid curves are generated by the line-shape fitting program described in section 7 of the text.
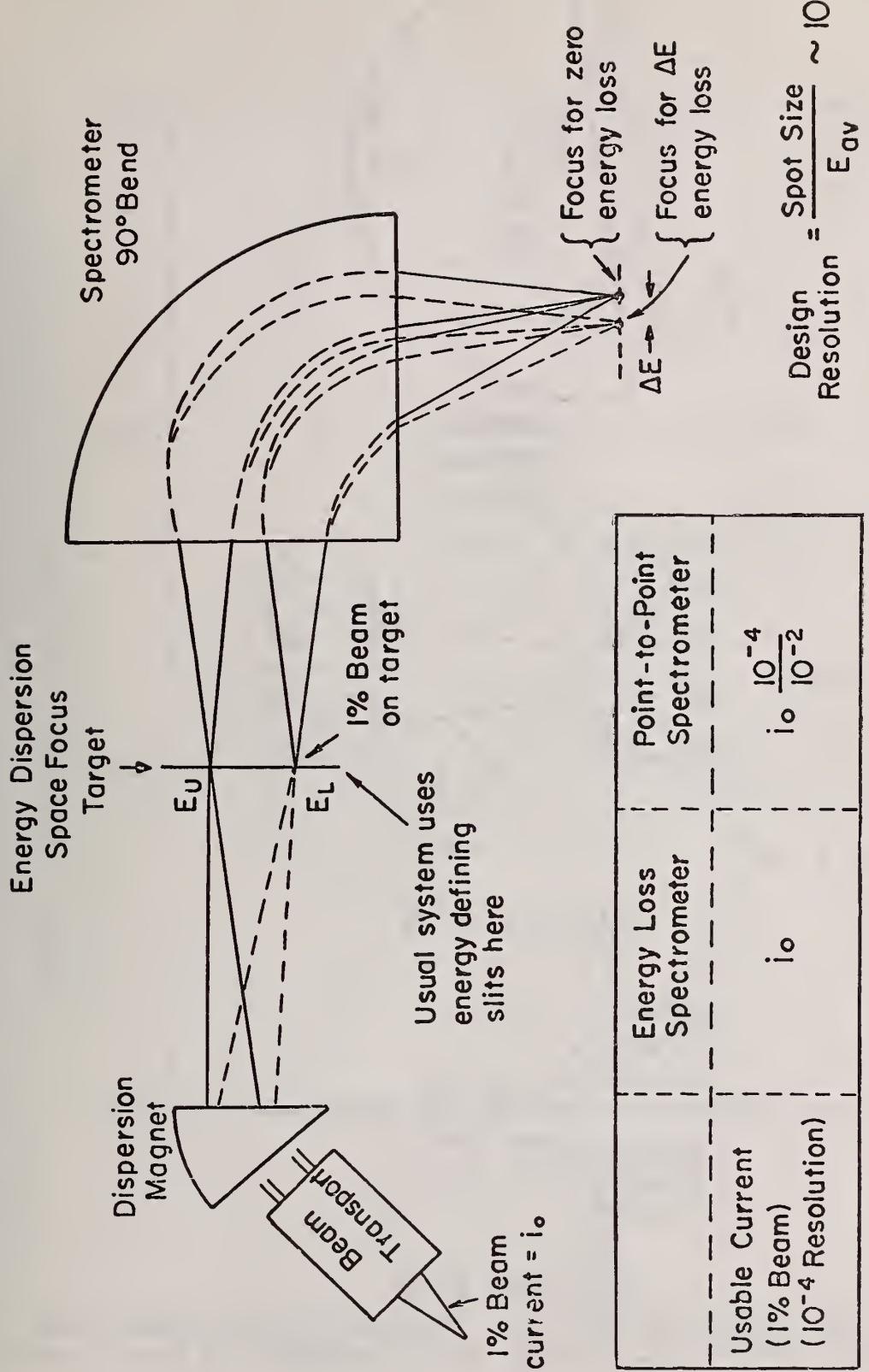
Figure 4. Principle of the MIT energy loss spectrometer system (see reference 8).
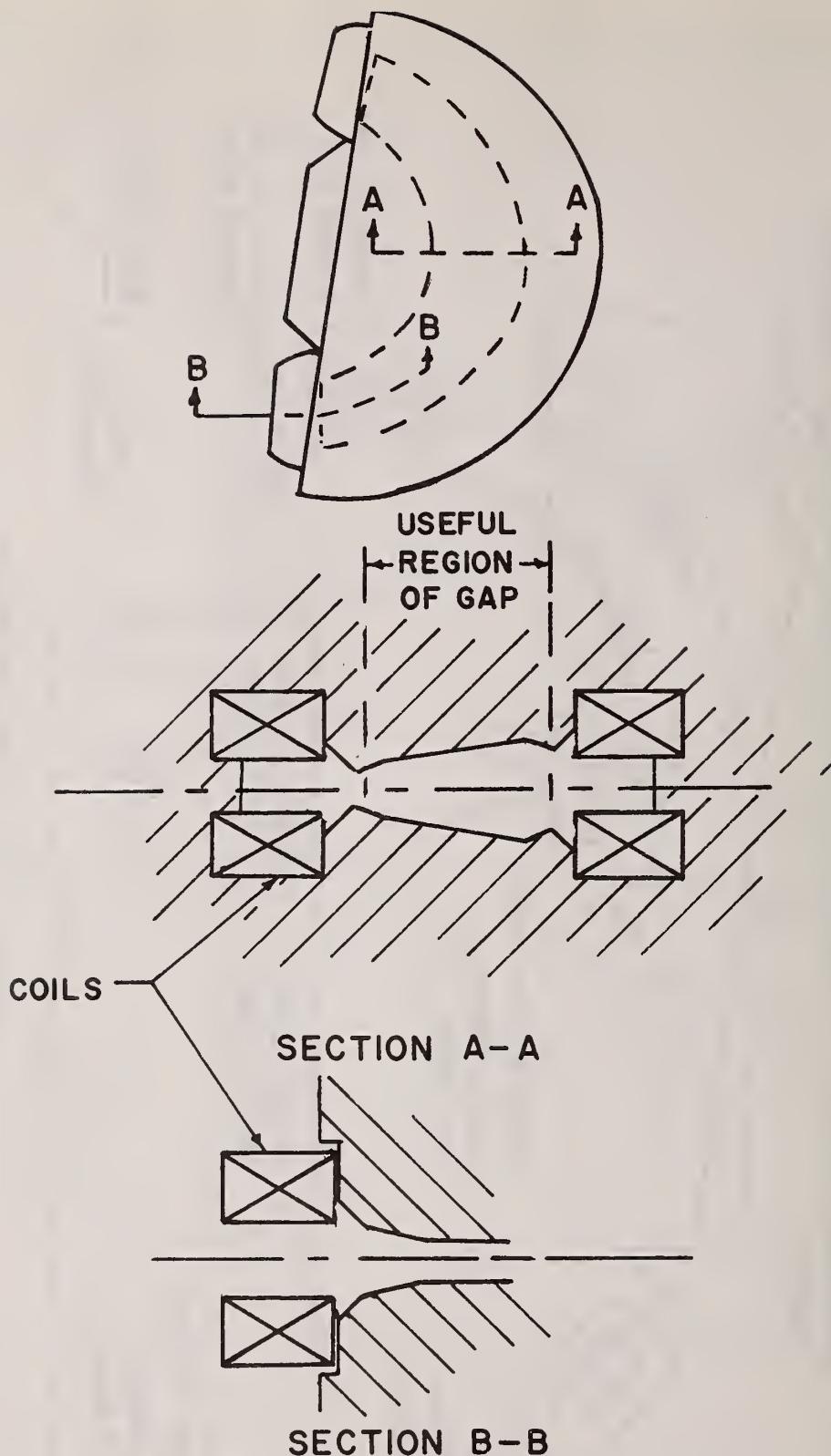
Figure 5. NBS spectrometer pole shape, illustrating the chamfered edges which result in a field distribution nearly independent of field strength.
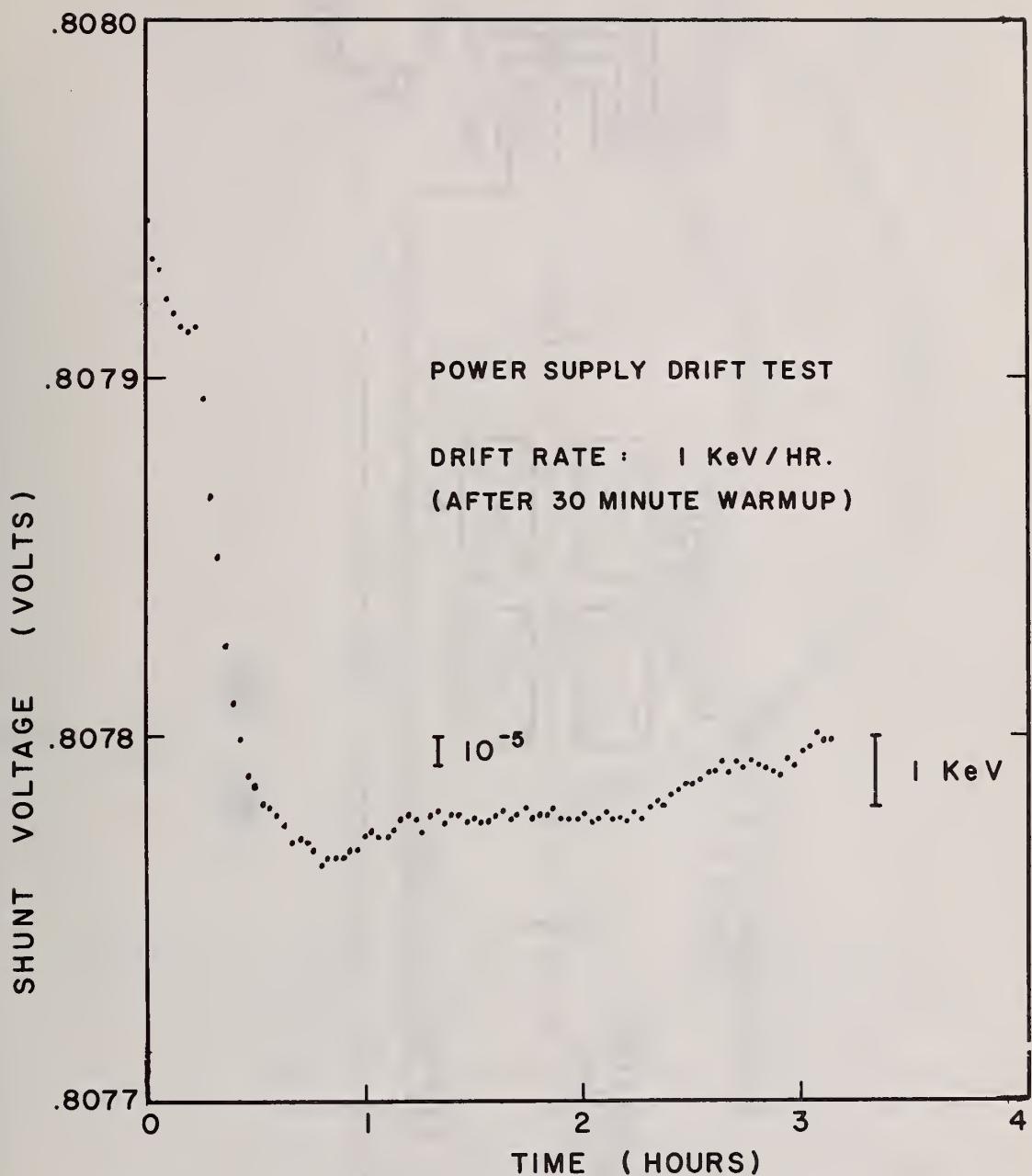
Figure 6. Current stability test of the NBS spectrometer and power supply. The labelled vertical bars show the shunt voltage changes which correspond to one part in 10^5 and one keV/C momentum changes.
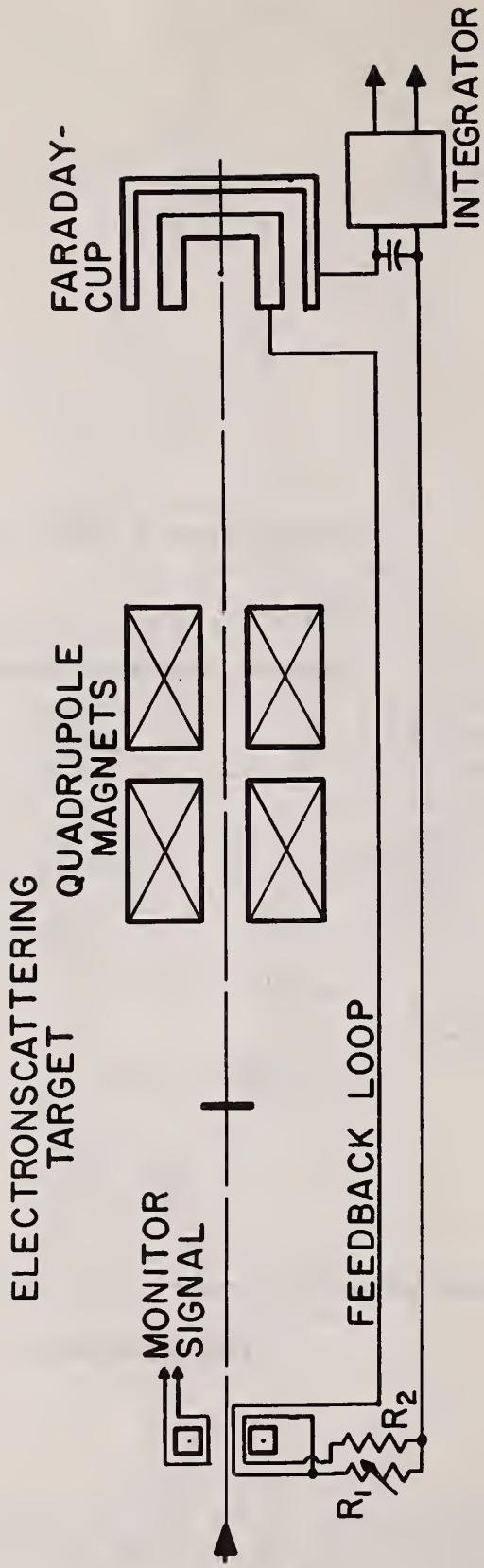
Figure 7. The Amsterdam beam current monitoring system. This figure is adapted from reference 24.

36
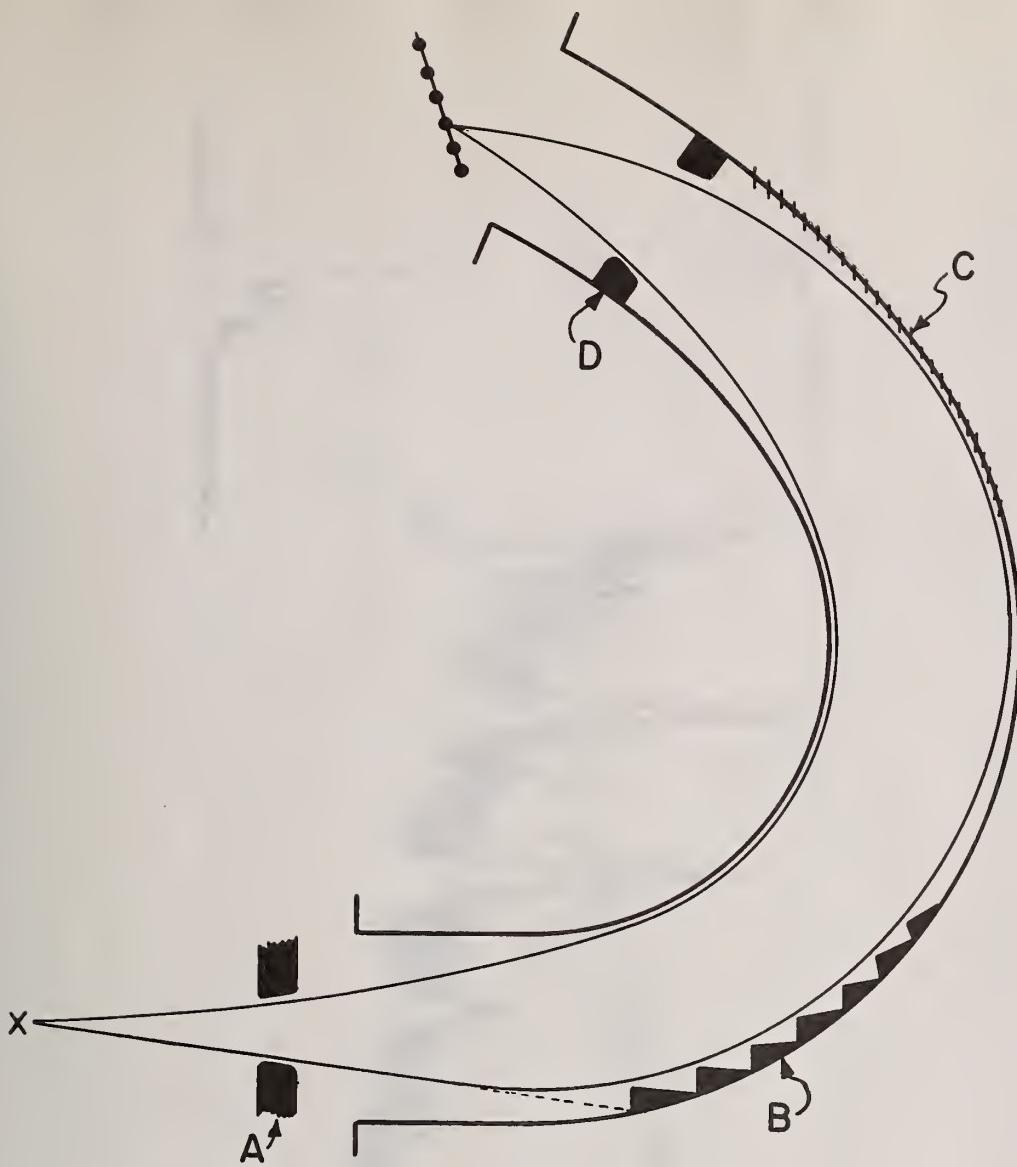
Figure 8. Baffling system on the NBS spectrometer. A tungsten and lead
collimator at A defines the vertical acceptance angle and
reduces the horizontal acceptance at this point. (The defini-
tion of horizontal acceptance is provided by the vacuum chamber
walls.) The lead "steps" at B are intended to absorb high
energy (e.g. elastically scattered) electrons when the mag-
netic field of the spectrometer is set for transmission of low
energy electrons. A low-Z liner at C reduces scattering of
electrons from the vacuum chamber. The lead aperture at D pre-
vents electrons from striking the vacuum chamber near the
detectors and also absorbs electrons previously scattered from
the vacuum chamber. Aperture D does not restrict the solid
angle for electrons headed towards the detectors. These meas-
ures together reduce the instrumental background by more than
a factor of ten.

37
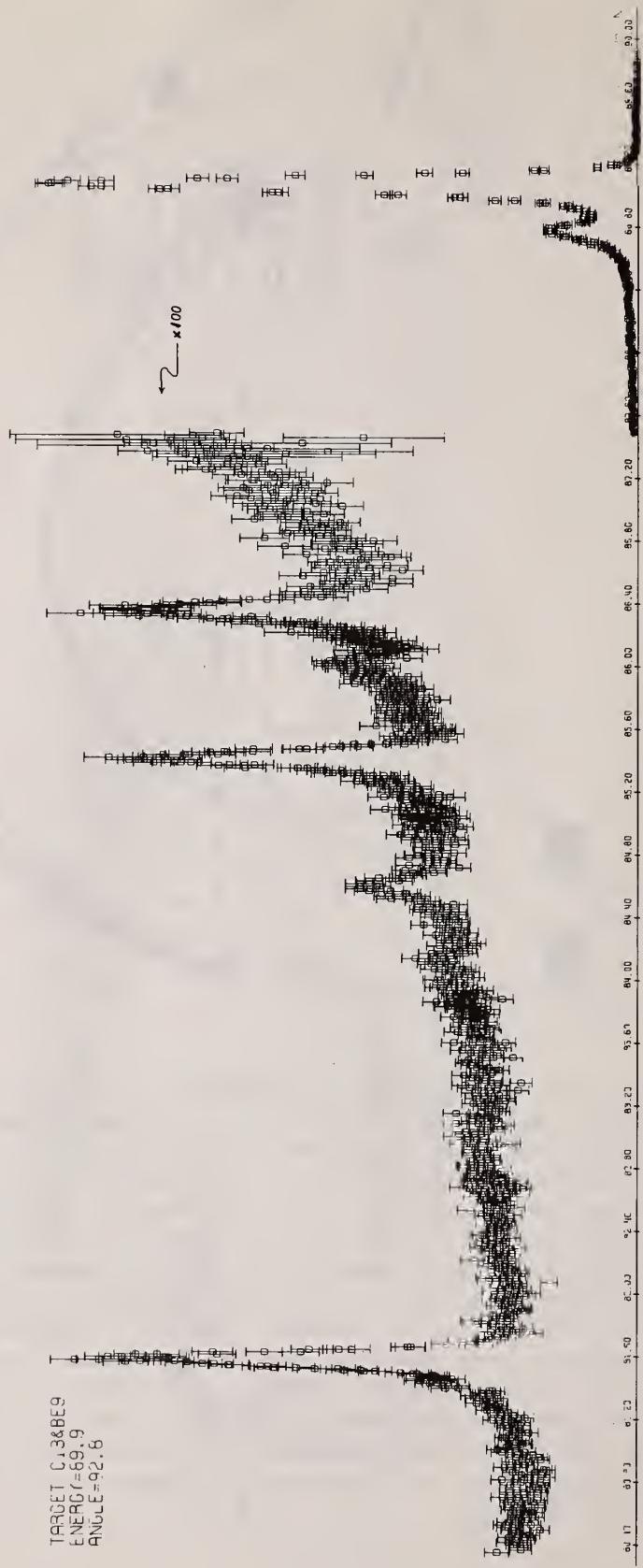
Figure 9. Spectrum of electrons scattered from a carbon 13 target. The cross sections for each detector in each run are plotted separately.

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TARGET: C13&BE9
ENERGY=89.9
ANGLE=92.8

× 100

Figure 10. The same data as in figure 9, with the results for all detectors combined and grouped in 20 keV bins. The carbon 13 compressed powder target has an 8% C^{12} contamination and is contained between thin beryllium windows. The main peaks in the spectrum, from right to left are: carbon elastic, beryllium elastic, Be-2.43MeV state, C^{13}-3.09 state, C^{13}-3.68MeV state, C^{12}-4.43MeV state, and C^{13}-7.5MeV levels. Data from reference 38.

39
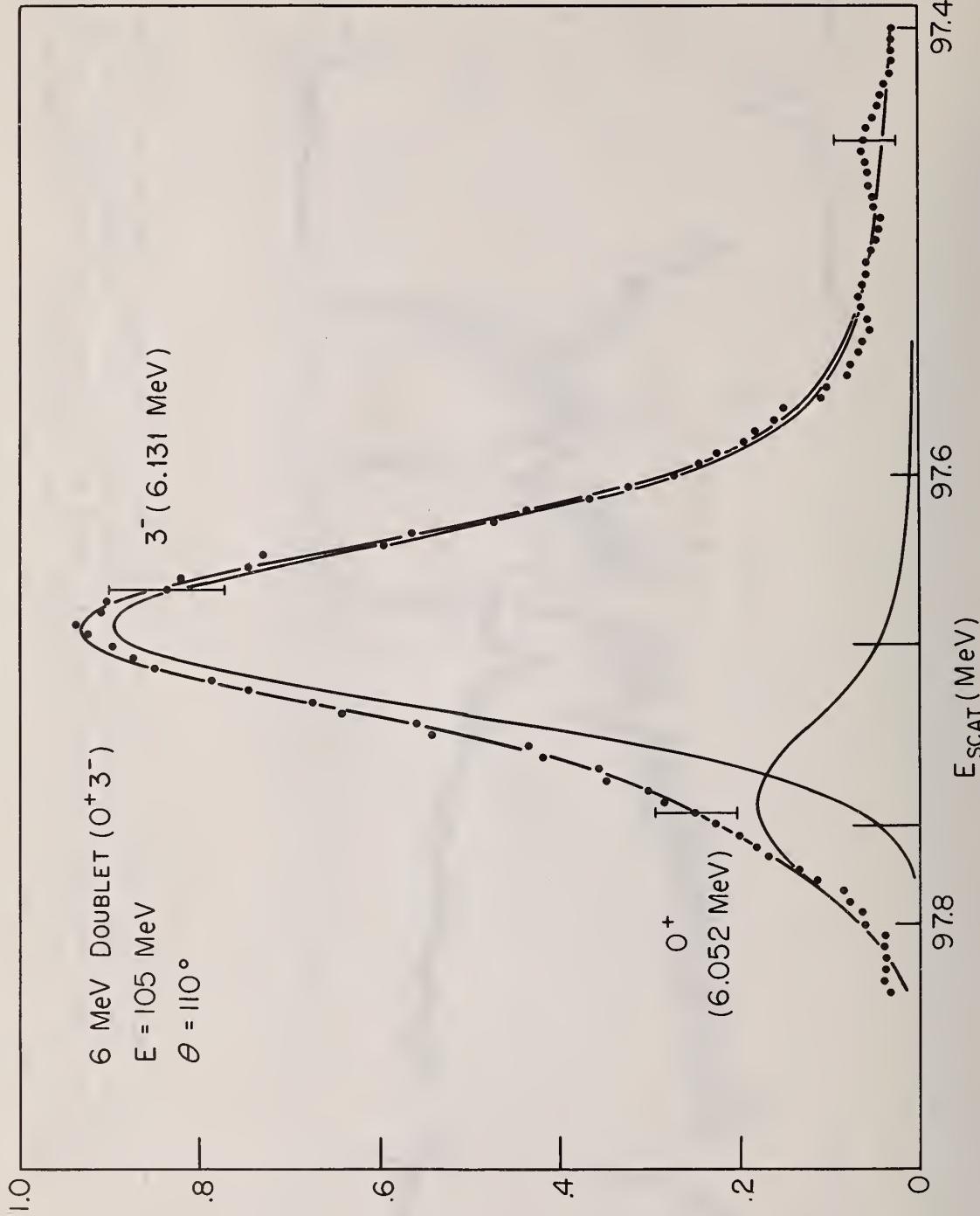
Figure 11. Same as figure 3, except the incident energy is 105MeV instead of 60MeV. The instrumental resolution is 85keV (.08%).
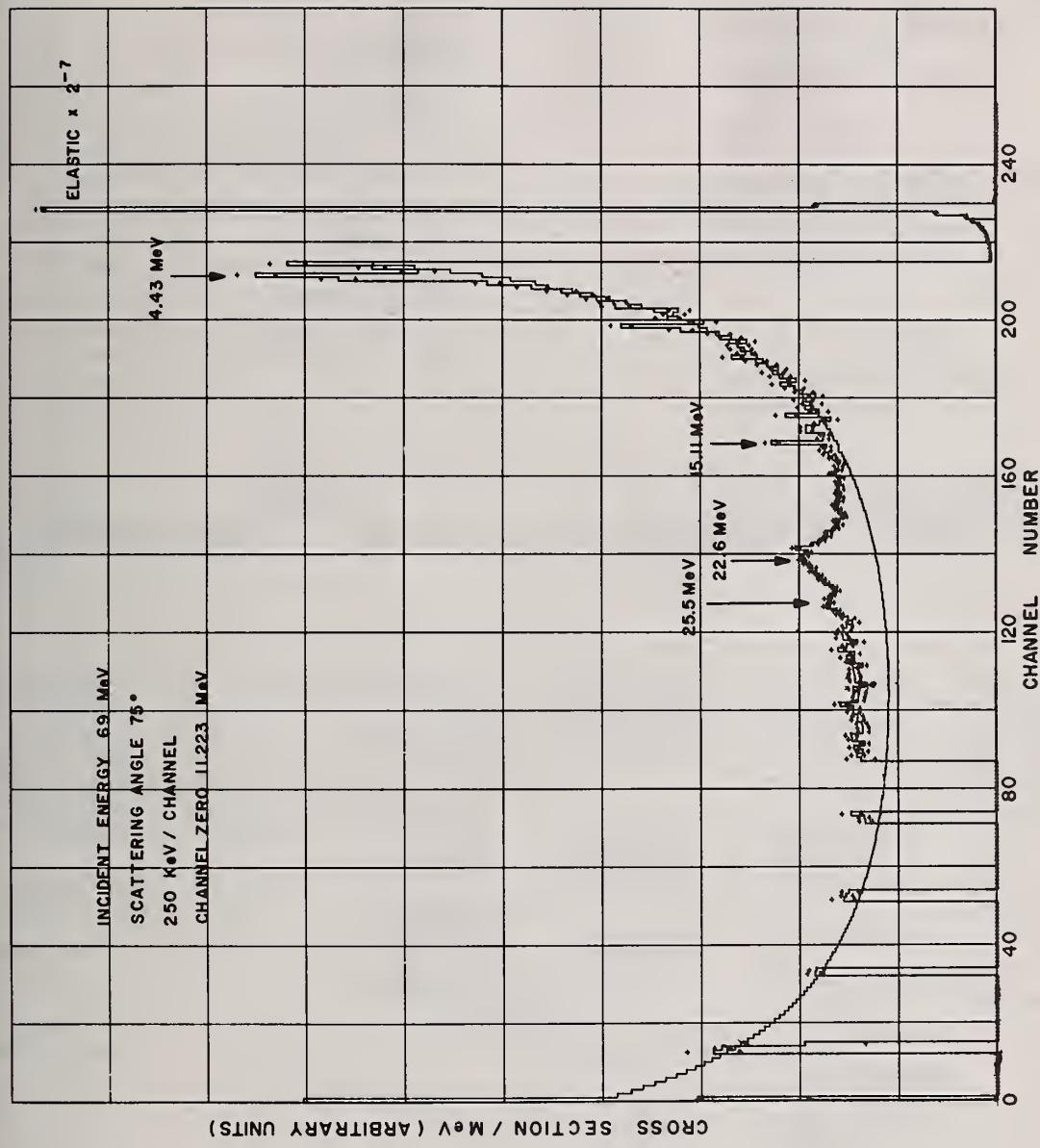
Figure 12. Spectrum of electrons scattered from C^{12}. The smooth curve is a complete radiative tail cal-culation, as mentioned in the text and described in detail in reference 12.

41
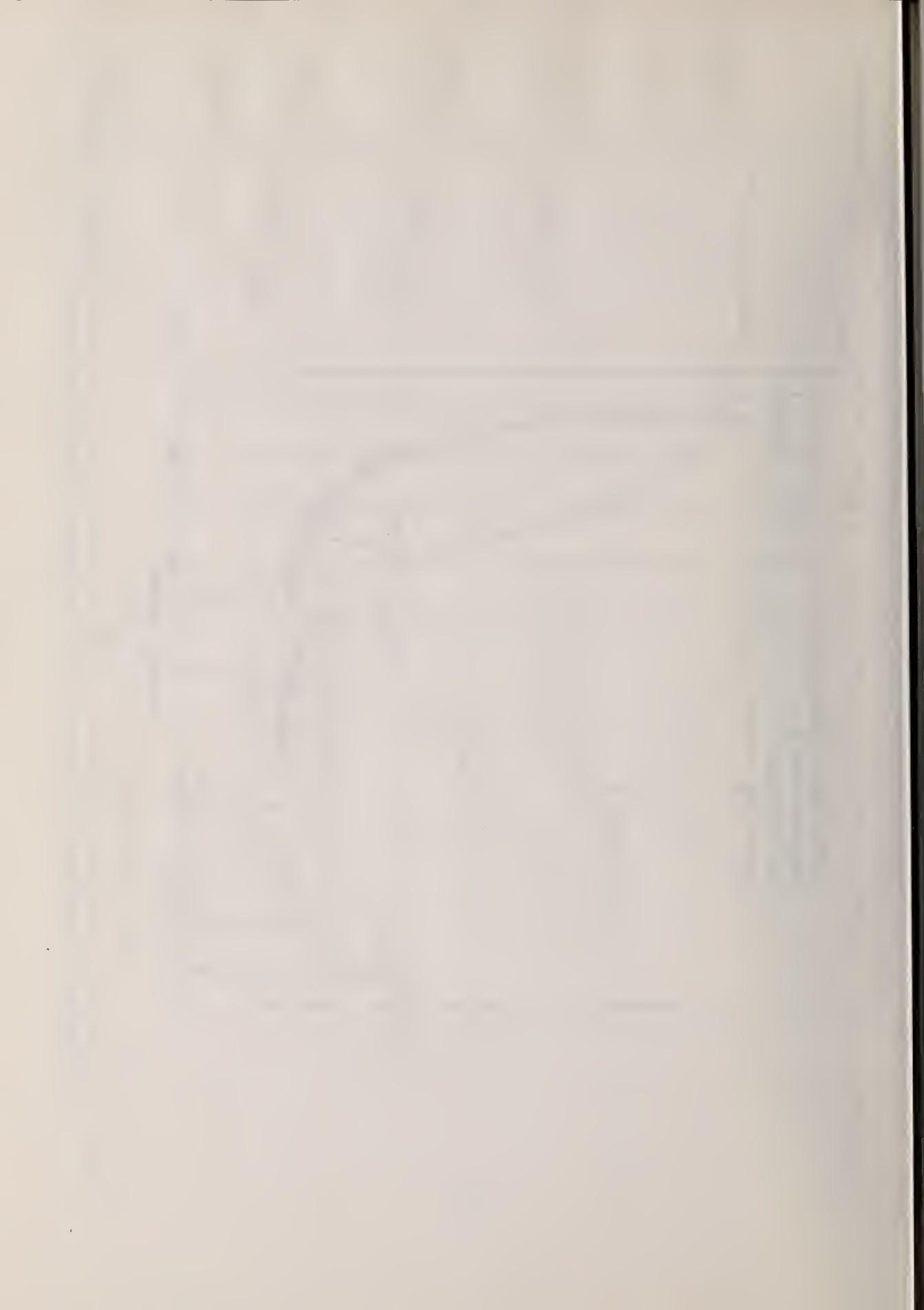
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NOTE: This schematic is neither an organization chart nor a program outline for budget purposes. It is a general statement of the Department's mission in relation to the national goal of economic development.

JULY 1969
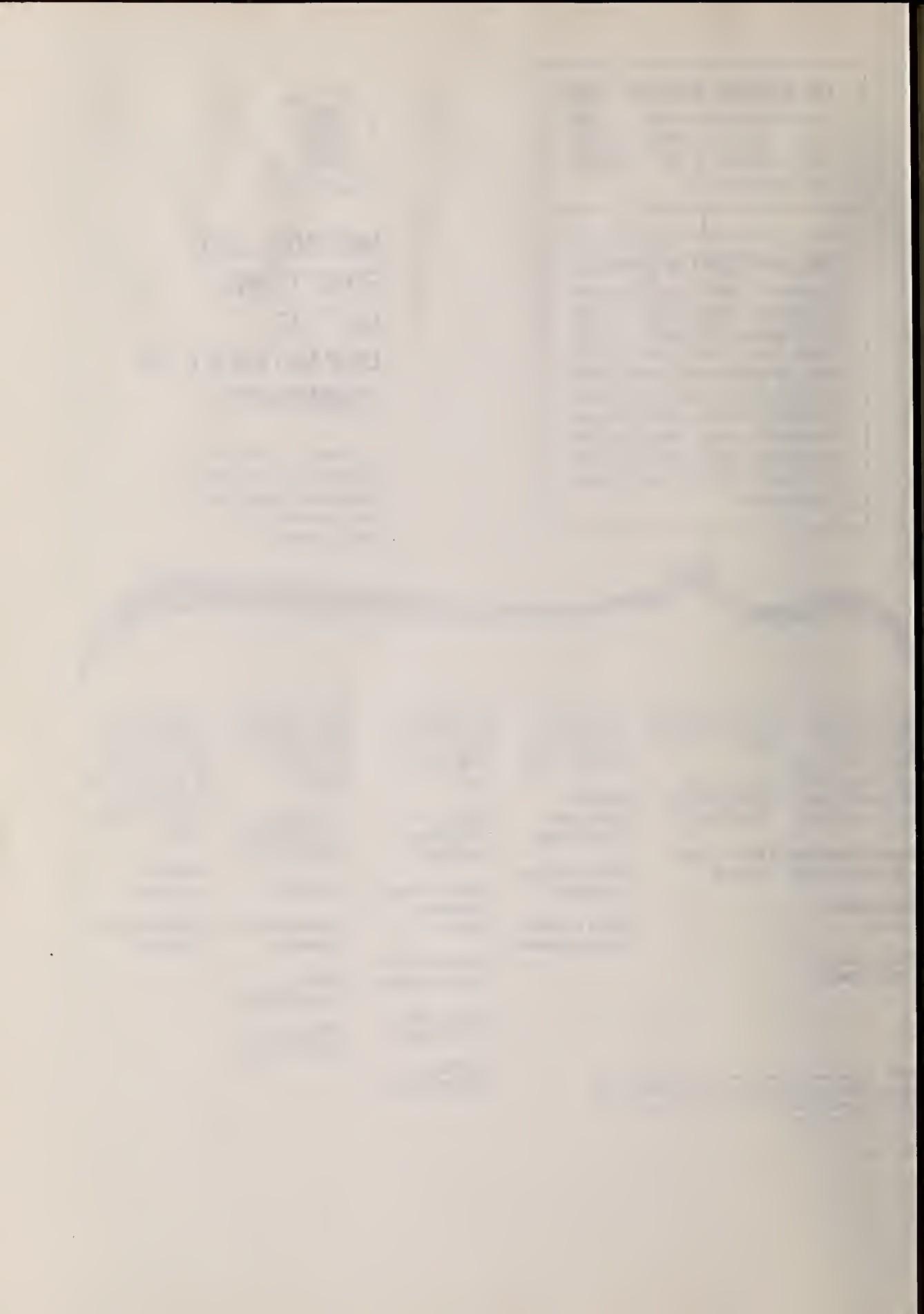
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